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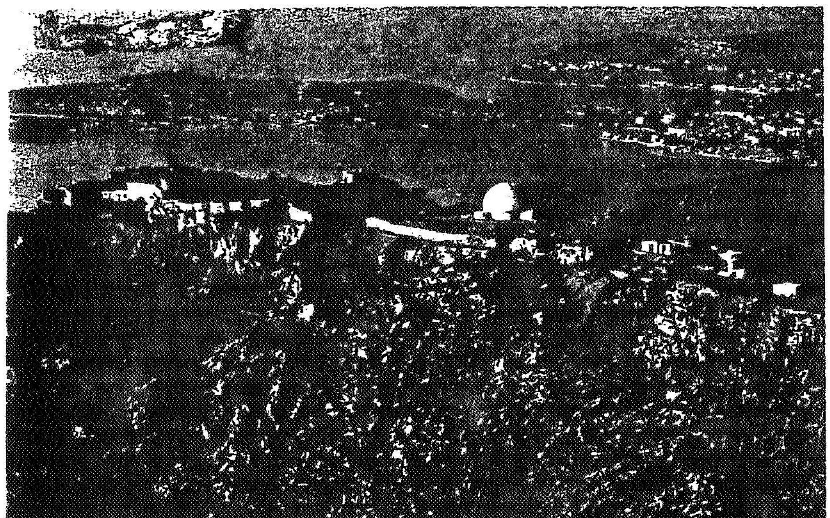

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A result of using the ray-casting visualization tool (*xlook*) to launch rays at a geometry, in order to analyze CAD-model integrity. See EM Programmer's Notebook.

Future Trends in Antennas and Propagation for the US Space Program

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1. Abstract

A key role of NASA (the US National Aeronautics and Space Administration) is to plan and execute programs, aimed at understanding the universe and matter, and the processes that underlie the development and evolution of life and the planet Earth. The part played by electromagnetic (EM) systems in information and energy transfer, and the tracking and imaging of objects and scenes, has been crucial to the successes of the space programs of various nations, to date. Indeed, the latest theories of the universe are based on the microwave-radiometer observations of the last two decades. The communications link, with manned and unmanned satellites, provides a crucial pathway for monitoring and controlling the health of these systems, as well as for transferring knowledge that is acquired by in-situ and remote observations. Previous space programs have also served the purpose of identifying the requirements for future electromagnetic systems, and associated techniques. In addition to small size, weight, and power consumption, the crucial requirements are in the radiation and thermal environment, in which the operation of these systems and the propagation of the EM waves should be assured. The Earth-observation applications of EM sensing include climate change, environmental monitoring, agriculture, geology, hydrology, urban planning, forest surveys, and ocean monitoring. Active- and passive-microwave, infrared, visible-band, and laser sensors will be used. Many emission, scattering, and propagation areas of EM research need to be addressed for these applications. Research and technique development will also be needed, in the areas of visualization and simulation, as tools for design and education purposes. New and innovative approaches, to the testing of propagation effects and antenna performance, can be developed through these software tools, in addition to training and education in the field of antennas and propagation.

2. Introduction

The technology drivers for NASA can be discussed in terms of the program, suggested by the Advisory Committee on the Future of the US Space Program [1], issued in December, 1990. The technology drivers include mission-to-planet-Earth and mission-from-planet-Earth programs, with the associated enabling infrastructure, space science, and management. These components can be viewed from a functional or from an infrastructure standpoint. In this case, the breakdown includes transportation, space sciences, exploration, space platforms, and operations. In the area of transportation, technologies are needed to substantially increase safety and reliability, and to provide new capabilities, while reducing life-cycle costs. Space science includes astrophysics, solar-system exploration, space physics, Earth science and applications, life sciences, microgravity science and applications, and communications- and information-systems research. The areas of NASA research include remote sensing, in-situ science, solar-system and outer-space observations, and communications and information systems. Those NASA advanced missions needing technology development include the Earth-observing systems, the large-deployable reflector, the Lidar atmospheric sounder and altimeter, the laser atmospheric-wind sounder, the geodynamics laser-gauging systems, the Mars rover sample return, the comet rendezvous and asteroid flyby, and the Lidar-in-space technology experiment. Advanced-instrument technologies and data systems needed for next-generation-observation systems include sensors and detectors, and optical systems. Communications and information systems are needed for near-Earth communication, space/terrestrial hybrid networks, and deep-space communications.

Space exploration encompasses human-support and surface operations. The needed capabilities include power systems, in-situ resource utilization, planetary rovers, surface construction and habitats, regenerative life support, radiation protection, intra- and extra-vehicular activity, communications, information management, man-machine interfaces, artificial gravity, and medical protocols. NASA's space platforms include Earth-orbiting platforms, space stations, and deep-space platforms. The technology drivers for these include advanced structures and materials, avionics systems, human support, communications and tracking systems, environmental interactions, propulsion and control, and power and thermal management [2].

Operations, as the term applies to the nation's civil-space program, constitute a broad spectrum of activities and associated facilities, which enable conducting a program or a mission so as to achieve desired goals and objectives. They include Earth-based, in-flight, in-space, and planetary-surface-based operations. The goal of the operations-technology development efforts is to provide systems, services, and the infrastructure to enable safe operations at a substantially reduced cost. The typical areas included are communications and information systems, automation and artificial intelligence, robotics and telepresence, training systems, human factors, life sciences, guidance, control, and navigation systems.

The future trends for antennas and propagation in space programs play a prominent role in three areas: information transfer, energy transfer, and remote-vision sensing. Associated with these applications of electromagnetic waves are propagation, scattering, and visualization and simulation. Figure 1 shows several unique characteristics, of planetary-surface and interplanetary regions, which have to be considered in developing analytical techniques and hardware. Furthermore, cost-effective approaches dictate small size, weight, and power consumption, and high reliability. Increased emphasis will be placed on reducing the costs of hardware development, through the innovative use of terrestrial systems which will meet space qualifications. In the terrestrial environment, the ionosphere and atmosphere provide unique interaction with electromagnetic radiation, which must be considered in future applications.

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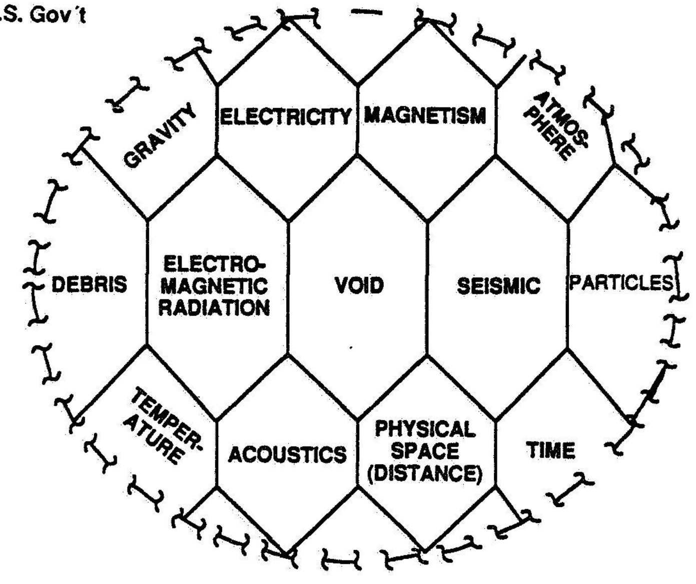

Figure 1. The space environment.

In view of the space-program requirements elaborated in this section, and the unique space environment, the fields of antennas and propagation will find great research challenges. As the limits of our exploration of the universe are extended through remote observations, the importance of EM research will increase immensely. This paper explores some trends in this research, based on the anticipated progress in exploration, in device development, and in fabrication, in various parts of the electromagnetic spectrum.

3. Information Pathways

The non-availability of communications-frequency ranges, for space-Earth interconnectivity, has encouraged the use of higher frequencies in the Ka-band (the 20 to 50 GHz region) [3]. One of the requirements for future communications satellites is multibeam antennas, which will provide frequency reuse, and will enable a 10- to 1000-times increase in the capacity of a single satellite in orbit. These systems will integrate growing microwave links. Geostationary (GEO) space-communication centers could enable global interconnectivity [4]. The technologies needed for these nodal satellites will include (1) on-board switching and signal processing, (2) electronically-hopped antenna beams, and (3) laser links to interconnect nodal satellites. Data rates for the interconnectivity will exceed two gigabits per second. These satellites will be capable of handling millions of subscriber lines, and hundreds of thousands of trunk or wide-band lines, in space. They will utilize thousands of spot beams, to interconnect Earth stations which are compatible, with terrestrial electro-optic networks. Millimeter waves and laser links will be used, to provide high-data-rate transfer between nodal GEO satellites.

For planetary and deep-space communications, higher microwave bands and laser implementations are desirable, because of the efficiency of information transmission. Due to the lack of atmosphere or very low atmosphere, path losses are negligible, and directed and small beam widths, and high data rates, can be realized through these systems. Microwave frequencies, in the range of 100 GHz to 1 THz, are projected [5]. Higher data rates are needed to accommodate remotely-sensed imagery in microwave, infrared, visible, and laser regimes. This includes data used for robotic vision, monitoring of planetary atmospheres and surfaces, and deep-space sensing. Both active and passive data will be acquired as a function of the angle of observation and polarization.

The observation of the Earth for the monitoring of climate, environment, and resources is an evolving field, with a wide range of applications. Sensors must be available in various parts of the EM spectrum. The parameters for these sensors will depend on the phenomenon under observation. The use of multi-frequency, multi-polarization, and multi-look-angle systems is essential, in many Earth applications. This will require extremely high data rates, in the tens of Gbps region, to acquire and transfer the data. Several propagation challenges must be addressed in the implementation of advanced communications systems. These include (1) mathematical modeling and measurement of interference levels, in the communications channel, due to other channels, multipath, passive emissions, and scattering; (2) accurate modeling of the effects of planetary atmospheres, terrestrial troposphere, ionosphere, and atmosphere; (3) accurate measurements of near fields, for far-field-pattern determination; (4) estimation of the effects of scattering and dispersion through optical fibers; and (5) developing techniques to discriminate between near and far sources. Many of these issues come up in finding the optimum placement of an antenna on a spacecraft or a planetary surface. In many applications, multiple beams, with precise pointing control, will be necessary at higher microwave bands and for laser communications. Understanding the effects of the space environment on pointing accuracy will be important in these applications. In some applications, tethers are used to generate power from the motion of the tether through plasmas. Reliable models are needed for tether interaction with a plasma. One exciting area is the modification of the Earth's and planetary ionospheres by heating, to allow communications with the least loss. Modulation of the ionosphere for desired propagation properties is not only important to the communications pathways, but also to their understanding and modeling.

Agile-beam, multi-polarization, and multi-beam-with-multi-frequency capability will also be essential to the implementation of future space-to-space, Earth-to-space, and planetary-surface-to-space/Earth communication systems (Figure 2). The antennas for this should have a very high reliability, with lifetimes of more than 20 years. For this reason, the effects of the space environment must

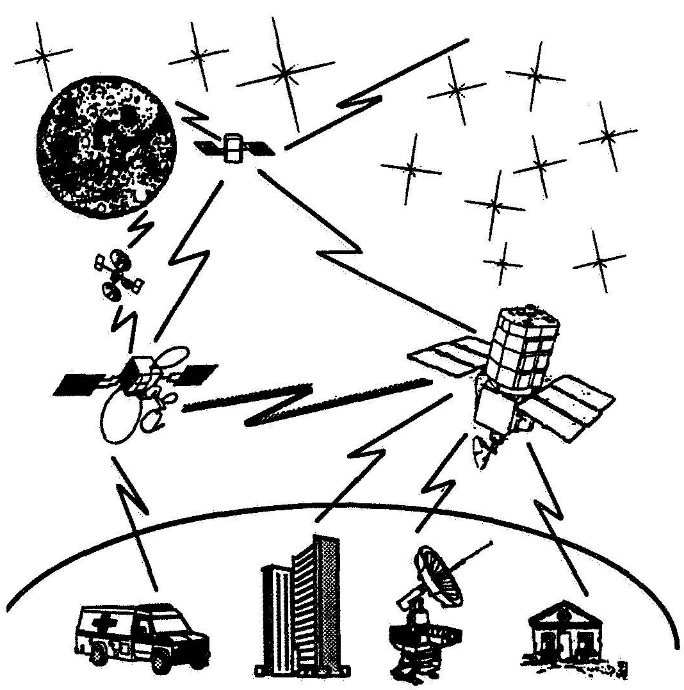

Figure 2. The future communications and tracking infrastructure.

be accurately understood, and appropriate hardware and techniques developed to mitigate these effects.

Vision and remote sensing

Numerous applications for robotic vision and remote sensing ıve been proposed for NASA programs. The robotic-vision ɔplications include inspection, maintenance, refurbishment, repair, ıel and materials transfer, detection of hazardous leaks, and ıtellite retrieval and servicing. In addition to this, vision data can e used in virtual-reality systems, to simulate the scene and its arameters to a higher degree of fidelity. The absence of nvironment causes light not to be diffused. This, in turn, creates ırge contrasts within an image. A secondary source of concern is he absence of gravity. For free-flying and tethered objects, there re an increased number of positions and orientations in which the ıbjects may be found, due to the lack of disturbances caused by ıerodynamics and gravitational forces. Consequently, objects must ıe recognized in any orientation for successful space applications. It hould also be noted that with an Earth orbit, the orbiting satellite ır space shuttle is in the absence of light for a portion of the orbit. 'or the lunar outpost, there is a lack of solar light for up to 15 days. n most of the robotic applications, very high resolution–from one ;entimeter to a few millimeters–is required.

The Earth-observation applications include environmental nonitoring, climate change, agriculture, geology, urban planning, ıydrology, forest surveys, and ocean monitoring. Mapping is also ıeeded at any location, any time of the day or night, to cover disas- :ers, both man-made and natural. Depending on the specific ıpplication, the revisit frequency to image a scene can range from laily to monthly. The resolution required ranges from one meter to greater than 15 kilometers, depending on the application.

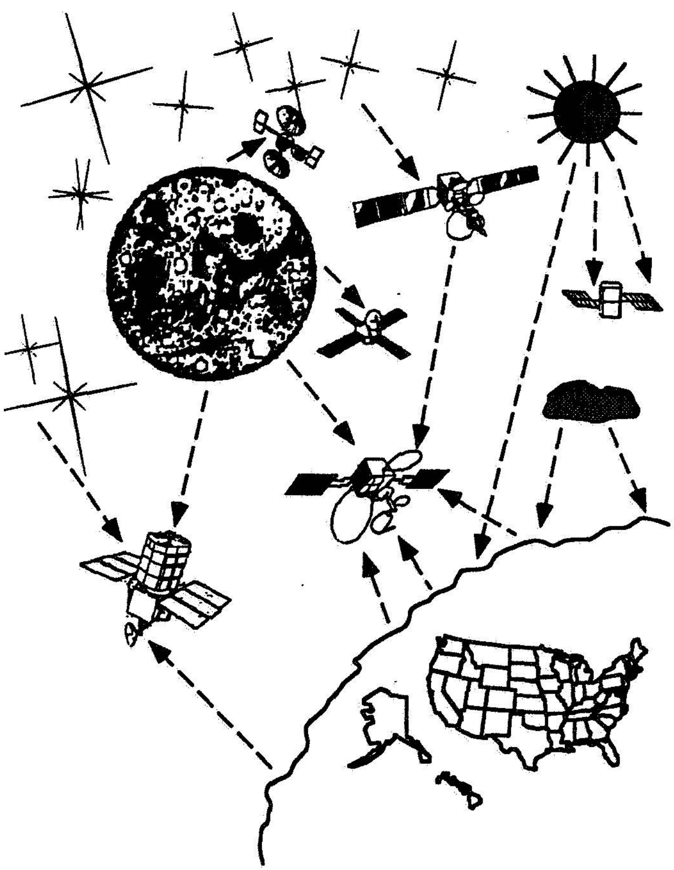

Figure 3. Remote-sensing and robotic-vision scenarios.

The proposed complement of sensors for robotic vision and remote sensing encompasses both active and passive microwave, infrared, visible band, and lasers [6]. More than 50 bands or frequencies at which these sensors should operate have been identified. In addition, these sensors are to operate at specific look angles, and to collect data for various polarizations.

Once again, remote sensing and robotic vision represent a formidable challenge to the antennas and propagation community (Figure 3). Scene and object recognition is performed on the basis of emitted or reflected and scattered EM radiation. To date, no accurate and reliable theories exist for the variety of objects and scenes which must be identified. The inverse-scattering problem has to be solved for inhomogeneous media, with varying surface-roughness scales. The inhomogeneties are not only to be modeled for the surface, but for the subsurface, as well. In particular, algorithms need to be developed for a combination of sensors, to identify an optimum set for the application at hand. This sensor fusion should recognize that synergism has to be exploited. Furthermore, because of the very high cost of space experiments, the analytical work must be of a sufficient accuracy to permit specifications and design for space-borne sensors. The effects of the ionosphere and the atmosphere must also be considered in these developments. Added to this is the challenge for innovative agile-beam, multi-polarization, and multi-frequency antenna design. For optical, infrared, and imaging microwave sensors, the resolutions must also be improved by tenfold over the current state of the art. The accurate location of the image on the ground, or of the object in space, is also vital to the success of the various applications. Thus, systems such as the Global Positioning System must be developed, in the future, to precisely locate a narrow antenna beam or a laser beam on the scene. This will require new and innovative uses of EM radiation and systems for space applications.

5. Energy transfer

From its inception, NASA has developed solar-power systems for satellites and spacecraft. This experience, coupled with the need for environmentally safe energy, led NASA to propose a Solar Power Satellite (SPS). The SPS was to convert solar energy into microwaves, and to transmit it to Earth stations for conversion, distribution, and utilization. This approach had several aspects which required research and experimentation. This program was not implemented, for reasons of cost, the impact of EM fields on humans and other forms of life, and impacts on the atmosphere. Subsequently, many studies have been carried out in the last two decades to explore the possibility of beaming solar energy, acquired on the Earth's surface, to power spacecraft in space, and also to provide alternative energy here on Earth. One of the ideas which is gaining momentum is the acquisition of energy at a convenient place in space, and subsequent beaming of it to satellites and spacecraft, using microwaves (Figure 4). In some cases, energy could be beamed from the Earth to spacecraft, to realize cost savings. These approaches to energy transfer and distribution rely on the accurate control of microwave beams. Furthermore, the interaction of EM fields with intervening media, and their effect on humans and other forms of life, must be understood through analysis and controlled experiments. The research needs in this area also include the design and development of antenna systems with extremely high efficiencies and precise beam-pointing control. Multi-beam antennas would provide simultaneous power to several desired locations and objects.

Other areas of research are electromagnetic interference (EMI) and electromagnetic compatibility (EMC). Power

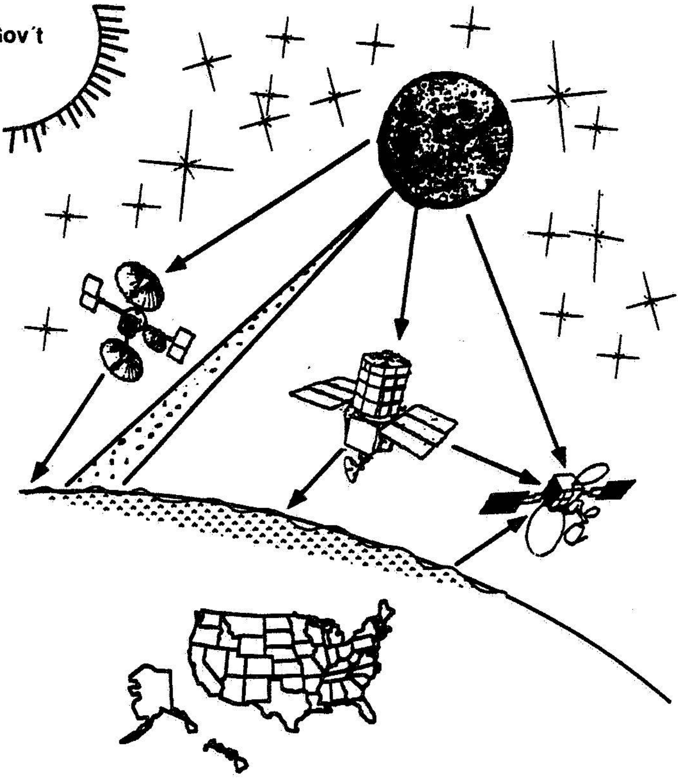

Figure 4. Power-transfer configuration possibilities.

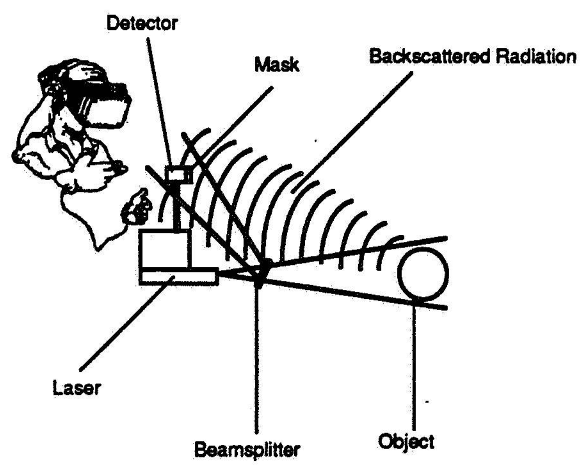

Figure 5. The visualization and simulation of holography.

transmission is usually done at very high levels, compared to communications transfers. Thus, interference issues can dominate certain configuration schemes. There is not only the need to accurately model EMI and EMC, but to provide techniques and systems to alleviate interference. In some planetary applications, the solar energy can be directly distributed, using optical fibers. In these applications, propagation and dispersion through fibers, and the transfer from and to the fibers, are the areas of future investigation. Optimization of energy transfer, without the adverse effects on fibers, should be the goal of these studies.

Research is also needed in the area of plasma excitation, to store energy for propulsion. This excitation is accomplished through radio-frequency coupling to the plasma, to generate higher kinetic energies for rocket propulsion. The efficient use of RF energy in these applications is key to the success of the rocket development. Advancements in this area include the use of superconducting-antenna coils and elements, and shaping of the RF field for maximum interaction with the plasma. The effects of polarization and frequency of operation of the RF field, for optimum performance, also have to be modeled and empirically demonstrated.

6. Simulation and visualization

With the advent of computers, and advancements in mathematical modeling, techniques for simulating system performance have become an essential design tool. These simulations are useful in developing the optimum design of the entire system, as a whole. Furthermore, the specifications on various components and subsystems can be identified, with an accurate representation of their performance in these simulations. With these simulations, needed technology developments can be identified. Furthermore, these simulations can be used to study failure mode(s), and components and subsystems causing abnormalities in the system performance. Virtual-reality techniques, coupled with accurate system performance, can provide a useful tool for education and training purposes. Near- and far-field, multipath and scattering, effects on and of intervening media, exposure of humans and other forms of life, effects of space environment, EMI and EMC, and other phenomena can be visualized through these techniques. System configurations can be changed to understand their effects on the overall performance (Figure 5). Antennas and propagation, as a discipline, needs such a training and education tool, since many of the EM radiation, emission, and scattering effects are invisible to the human eye. Furthermore, in space applications, these tools are necessary to train astronauts and mission specialists, so that construction and servicing of space-borne and planetary-surface systems can be accomplished most efficiently. This aspect of EM propagation is still largely unexplored. However, most of the tools and infrastructure are available to begin experimenting with virtual reality, as a training and education tool.

7. Conclusion

The future trends in antennas and propagation have been identified in the areas of communications, vision and remote sensing, energy transfer, and simulation and visualization. Future space-communications systems can be in the frequency regime of 20 GHz to 1 THz. In addition, coherent laser-based photonic systems will also be explored. The use of polarization to increase information-transmission rates will also be investigated. Antenna technology for broad-band, low-loss transmission and reception will incorporate new and advanced microstrip, phased-array designs, using high-temperature-superconducting materials and devices. These advanced-antenna systems will be used to acquire active- and passive-sensor data, in the near and far zones, for object- or scene-parameter determinations. These parameters include range, velocity, orientation, dielectric constant, and surface roughness. Vision systems, based on this technology, can be used in Earth and space observations, as well as space-robotic systems. The use of EM waves, in the microwave bands, for the transmission of energy, will be important for future space programs. Many concepts for the conversion and beaming of solar energy from space to Earth, or from one location to many locations in space, have been advanced in the past decade. Their practical manifestation will depend on the efficiency and safety with which the energy can be transferred. Associated with the many applications of EM systems to space, research will need to be conducted in the propagation of EM waves in terrestrial and extraterrestrial environments, in EM compatibility,

multipath and scattering effects, and in human exposure to EM radiation. A crucial aspect will deal with the testing of hardware systems, so that their space performance can be assured for long periods, lasting up to 20 years. In this regard, new and efficient techniques need to be developed for ground and space testing. Visualization and simulation tools will be needed for design, training, and education purposes. Extensive research is needed in this area.

8. Acknowledgment

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Introducing Feature Article Author Kumar Krishen

Kumar Krishen is the Chief Technologist, New Initiatives Office, for the Johnson Space Center (JSC). He is responsible for developing strategies for joint research and technology projects, and plans with other NASA centers, universities, and other government agencies. He is also responsible for assisting advanced-technology planning for the Center and the Agency. He represents JSC as the Principal Technologist on the NASA Council on Science and Technology. Prior to this, he was the Assistant to the Director for Technology and Advanced Projects for the Mission Support Directorate.

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